High-Mg adakites from Kadavu Island Group, Fiji, southwest Pacific: Evidence for the mantle origin of adakite parental melts

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ABSTRACT

We report here the compositions of primitive high-Mg adakite lavas from the Kadavu Island Group, Fiji. Two distinctive high-Mg adakite compositions are present on Kadavu, and both are strongly enriched in Sr and La, with high Sr/Y (>120) and La/Yb (>30) values. The east Kadavu high-Mg adakite is relatively enriched in K_2O and depleted in TiO_2 and Nb. Our results from Kadavu suggest that there is an adakite magma series that is the result of complex open-system magmatic processes, including magma mixing between relatively low SiO_2 mantle-derived melts of high-Mg adakite composition and high SiO_2, low-Mg adakite magma. The results from Kadavu Island suggest that adakite magma suites worldwide are likely to include primitive high-Mg compositions, despite the lack of field evidence in many cases.

Keywords: adakite, olivine, melt inclusions, Kadavu, Fiji, slab melting, hot subduction.

INTRODUCTION

Adakites are a subduction-related magmatic rock suite that has chemical features consistent with melting of subducted oceanic crust (Kay, 1978; Defant and Drummond, 1990; Martin et al., 2005). Adakites are classified mainly on the basis of trace element abundances and ratios, their high Na_2O and low FeO also being typical features. Martin et al. (2005) proposed a subdivision of adakites into two groups: low SiO_2 adakites (LSA, <60 wt% SiO_2) and high SiO_2 adakites (HSA, >60 wt% SiO_2). The LSA are more magnesian. Some are compositionally high-Mg andesite (e.g., bajaites, Baja California, Mexico; Rogers et al., 1985; Calmus et al., 2003; adakites from Adak Island, Aleutians; Kay, 1978; Yogodzinski and Kelemen, 1998; Kelemen et al., 2003), whereas others are high-Nb basalts (e.g., Kamchatka; Kepezhinskas et al., 1997). The HSA, in contrast, are generally low-Mg andesites, dacites to rhyolites, rarely associated with more primitive magma compositions (Defant and Drummond, 1990; Defant et al., 1991). The LSA in general are more enriched in incompatible elements compared to HSA, especially Sr, La, Ti, and Nb.

Distinct petrogenetic models were proposed for the HSA and LSA. The HSA are believed to represent partial melts of the basaltic crust within the subducted slab, and their compositions are consistent with melting of eclogite and/or amphibolite, as demonstrated in several experimental studies (see Martin et al., 2005, for discussion). In contrast, incompatible element–enriched high-Mg LSA compositions cannot be direct slab melts, but instead are believed to be the result of melting of a mantle wedge previously metasomatized by the addition of slab-derived melts (Stern and Kilian, 1996; Martin et al., 2005). Detailed studies of mantle xenoliths, representing samples of metasomatised mantle wedge peridotite, support this model for LSA petrogenesis (Schiano et al., 1995; Kepezhinskas et al., 1995; Kilian and Stern, 2002; Wang et al., 2007).

Other workers have argued that some adakitic rock suites are not the result of slab melting, but instead may have been generated by melting of deep crustal metabasic rocks (Atherton and Petford, 1993), or they may reflect either low-pressure assimilation–fractional crystallization (AFC) processes (Castillo et al., 1999) or high-pressure crystallization involving garnet (Macpherson et al., 2006) of typical subduction-related magmas derived from melting of the mantle wedge.

This paper reports the compositions of rare high-Mg adakites from the Kadavu Island Group, Fiji (GSA Data Repository Fig. DR1[1]). The detailed petrology of the Kadavu Island adakite magma series will be presented elsewhere. These high-Mg adakites are typical LSA and represent primitive mantle-derived magmas clearly associated with the more evolved adakite magmas reported from Kadavu (Verbeeten et al., 1995; Verbeeten, 1996; Crawford and Verbeeten, 1997), forming together a continuum of compositions (Fig. 1; Fig. DR2) that indicates the existence of a magma series. The low-Mg adakites from Kadavu are typical HSA, and our results suggest that the petrogenesis of most HSA will involve more primitive high-Mg LSA compositions. We therefore propose that adakites form a distinct subduction-related mantle-derived magmatic suite, the petrogenesis of which involves melting of a mantle wedge metasomatised by a slab melt component, and that their subdivision into LSA and HSA does not have genetic significance.

Primitive olivine + clinopyroxene-phyric adakites were discovered in eastern Kadavu in 2003 (ST43, ST44 in Table 1; Fig. DR1). These lavas crop out in a restricted area around Uthuinanggaralevu Point (Fig. DR1), between the villages of Tioma and Nathomoto. The lavas from this area also include typical low-Mg HSA, forming together a single lava series (Nungganungga volcanic unit; Woodrow, 1980). The Ngaloa LSA are olivine + clinopyroxene ± plagioclase ± phlogopite – phyric basalts to basaltic andesites and were reported as high-Nb basalts by Crawford and Verbeeten (1997). The geological setting of Kadavu is presented in the GSA Data Repository along with detailed petrographic descriptions and locations of our samples.

GEOCHEMISTRY AND MINERALOGY

In Table 1 and Figures 1–3 we present major and trace element and isotopic compositions of the high-Mg adakites from the Kadavu Island Group. (For the complete set of analyses from the Kadavu Island Group, see the Data Repository.) Two distinct end members can be identified among high-Mg adakites; the eastern Kadavu (samples ST43 and ST44) and the Ngaloa (samples NG1 and NG4). Olivine phenocryst cores in the east Kadavu high-Mg adakites range in composition from ~Fo_{84} to Fo_{94} (Fig. 1B), and show slight normal zoning with a range of 1–2 Fo units. Olivine phenocrysts contain primary melt inclusions with typical adakite compositions (Fig. 2B), indicating that olivine crystallized from an adakite melt. Olivine also contain Cr-spinel inclusions with Cr# of ~80–87. Clinopyroxene phenocrysts are also normally zoned with cores having an Mg# range of ~68–92.

The Ngaloa high-Mg adakites have a more restricted range in olivine phenocrysts compositions, ~Fo_{85-91} (Fig. 1B). These also contain primary melt inclusions of adakite compositions (Fig. 2C). Clinopyroxene phenocrysts show a range in composition from Mg# ~65 to 91,

[1]GSA Data Repository item 2008118, major and trace element geochemistry of Kadavu adakites, supplementary figures, geological setting, petrographic descriptions, analytical techniques used, and supplementary discussion, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

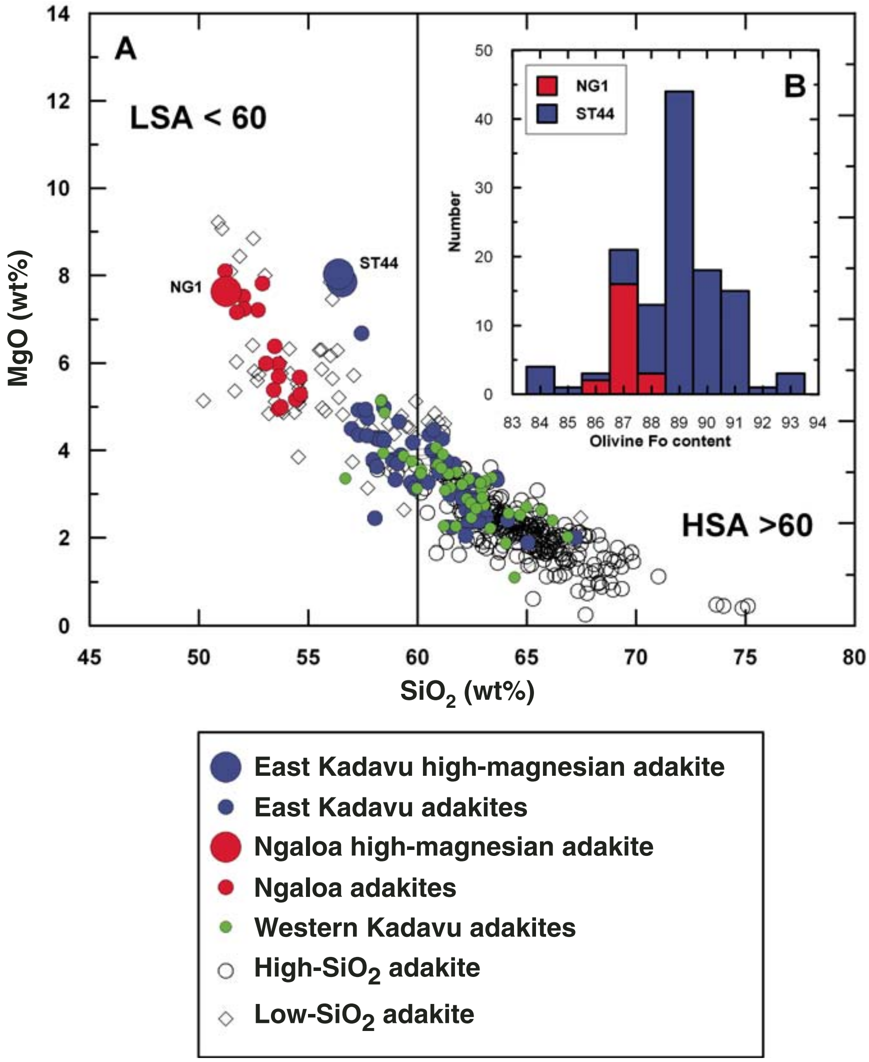

Figure 1. A: MgO wt% versus SiO_2 wt% for Kadavu adakites compared to adakites worldwide. High SiO_2 (HSA) and low SiO_2 (LSA) adakite data and boundary between HSA and LSA at 60 wt% SiO_2 are from Martin et al. (2005). The high-Mg adakites from this study are labeled (NG1 and ST44; Table 1). For Kadavu data, see footnote 1. B: Olivine phenocryst histogram of olivine core compositions in high-Mg adakite samples NG1 (Ngaloa) and ST44 (eastern Kadavu).

with either normal or reverse zoning. Reversely zoned clinopyroxene contains cores of Mg# ~70–75 with rims of Mg# ~86–91. The Ngaloa high-Mg adakites also contain rare phenocrysts of plagioclase ($An_{30–70}$) and phlogopite. The phlogopite is commonly found intergrown with clinopyroxene and olivine in glomerocrysts, or as a reaction rim on olivine phenocrysts.

In terms of the key major and trace element indices, both the east Kadavu and Ngaloa high-Mg adakite compositions are classified as LSA (Martin et al., 2005; Fig. 1A; Fig. DR2). Together with the low-Mg adakites from eastern and western Kadavu, the entire spectrum of lava compositions from the Kadavu Island Group almost encompasses the global range of adakite compositions (Fig. 1A; Fig. DR2). Figure 1A indicates that in the case of the Kadavu adakites, the division into LSA and HSA types is clearly arbitrary, and in reality we see an adakite magma series, with a continuous range from relatively high to low MgO compositions. We therefore refer to the Kadavu adakites as either high-Mg or low-Mg adakites.

In Figure 2A the trace element abundances of the Kadavu high-Mg adakites are compared to the average abundances for HSA and LSA compiled by Martin et al. (2005). The Kadavu high-Mg lavas are typical adakites, with high Sr/Y >130 and La/Yb >30 values. They also show depletions in Ti and Nb relative to the large ion lithophile and rare earth elements (REE), and an enrichment in Zr relative to Sm. These same features are shared by the olivine-hosted melt inclusions (Figs. 2B, 2C). Compositions of melt inclusions in the east Kadavu adakite olivine correlate with the host compositions; inclusions in high-Fo olivine have higher abundances of incompatible elements and Sr/Y and La/Yb values compared to lower-Fo olivine (examples are given for two individual inclusions in Fig. 2A). The Kadavu high-Mg adakites have isotope values similar to the radiogenic end of the Pacific mid-oceanic ridge basalt (MORB) field in Sr-Nd-Pb space (Table 1).

DISCUSSION AND CONCLUSIONS

Detailed studies of high-Mg andesites and adakites suggest that the compositions of these magmas reflect complex open-system processes such as magma mixing, and combined assimilation–fractional crystallization (Yogodzinski and Kelemen, 1998; Streck et al., 2007; Ohba et al., 2007; Guo et al., 2007). Some high-Mg andesites may, in fact, not represent a primary mantle–derived magma. For example, Streck et al. (2007) demonstrated that high-Mg andesites from Mount Shasta are hybrid magmas resulting from the assimilation of mantle xenolithic material combined with the mixing of normal arc basaltic magmas with evolved dacitic to rhyolitic compositions.

In the case of the newly discovered high-Mg adakites from Kadavu, all of the magnesian olivine phenocryst phases crystallized from an adakite melt, as demonstrated by the presence of primary melt inclusions with strong adakitic signature (Figs. 2B, 2C). This result clearly demonstrates the existence of primitive high-Mg adakitic magmas and is consistent with other studies that argued the existence of high-Mg, Sr- and light REE–rich adakitic magmas (Yogodzinski and Kelemen, 1998; Guo et al., 2007).

The Kadavu adakites, and the eastern Kadavu adakites in particular, are characterized by unusually high K contents (Table 1; Fig. DR2D). This is likely a specific feature of the mantle source of these magmas, as contemporaneous shoshonites are present immediately north of eastern Kadavu (Table 1; Fig. DR1). However, high-Mg adakites are clearly distinct from absarokites, the high-Mg end member of the shoshonite magmatic series. Characteristic features of high-Mg adakites include very high Na_2O, high SiO_2, and very low FeO^T and low CaO contents, atypical for absarokites (Table 1). Adakites also have significantly higher La/Yb values (Fig. 2A) and significantly lower Ba/Th values, indicative of enrichment by melt rather than fluid, which is typical for absarokites. Absarokites also do not display enrichment of Zr over Sm, and have more radiogenic Sr isotopes for a given Nd isotopic composition (Table 1), typical of most subduction-related lavas, whereas adakites are characterized by MORB-like isotopic values.

Within the Kadavu adakite series, the extent of adakite signature (e.g., Sr/Y and La/Yb values, and overall enrichment in incompatible elements) increases with increasing MgO content (Figs. 2A and 3C). The high-Mg adakites have higher Sr/Y and La/Yb values than low-Mg adakites, whereas melt inclusions in high-Fo olivines, which record melts more primitive than those that formed the

TABLE 1. WHOLE-ROCK MAJOR ELEMENT AND ISOTOPIC GEOCHEMISTRY OF HIGH-Mg ADAKITES AND SHOSHONITE FROM THE KADAVU ISLAND GROUP

Major element (wt%)	High-Mg adakites sample number				Shoshonite* sample number
	ST43	ST44	NG1	NG4	AV186
SiO_2	56.53	56.39	51.25	52.03	47.92
TiO_2	0.62	0.61	1.69	1.69	0.65
Al_2O_3	14.59	14.56	16.19	15.56	10.34
FeO^T	5.50	5.52	6.80	6.36	10.07
MnO	0.10	0.10	0.11	0.1	0.19
MgO	7.86	8.03	7.63	7.52	11.52
CaO	7.62	7.65	9.99	10.26	12.7
Na_2O	3.84	3.82	3.83	3.99	2.17
K_2O	2.86	2.82	1.70	1.65	1.33
P_2O_5	0.49	0.49	0.81	0.84	0.24
LOI	0.70	0.61	0.67	0.57	2.15
Mg#	0.718	0.722	0.667	0.678	0.671
Isotope analyses					
$^{87}Sr/^{86}Sr$	0.703158	0.703138	ND	0.702946	0.70411
$^{143}Nd/^{144}Nd$	0.513038	0.513037	ND	0.513050	0.51298
$^{206}Pb/^{204}Pb$	18.866	18.875	ND	18.833	18.79
$^{207}Pb/^{204}Pb$	15.553	15.552	ND	15.549	15.528
$^{208}Pb/^{204}Pb$	38.443	38.449	ND	38.417	38.548

Note: ND—no data; LOI—loss on ignition; major element analyses have been resumed to 100% anhydrous with all Fe as FeO (FeO^T).
*Sample AV186 from Leslie (2005).

sampled high-Mg adakite lavas, have even higher values of these ratios (Fig. 3C).

It is thus clear that magma evolution processes responsible for the formation and eruption of the adakite series lead to dilution of the adakite signature. The exact nature of these processes remains unresolved and is the subject of our continuing investigations. A possible model is detailed in the following.

The Kadavu adakite suite demonstrates clear evidence for magma mixing, including mineral compositional trends, whole-rock trends of the adakite suite as a whole, and the compositions of Ngaloa-type high-Mg magmatic enclaves present within the western Kadavu low-Mg adakites. The K_2O contents of the Kadavu Island Group lavas are presented in Figure 3A. In general, closed-system crystal fractionation of the observed phenocryst phases will cause increasing K_2O contents with increasing SiO_2, and this is seen in the overall trends of whole-rock compositions for the Astrolabe shoshonites and the adakites of eastern and western Kadavu. However, both the east Kadavu and Ngaloa high-Mg adakites do not have appropriate SiO_2 and K_2O contents to be related to the low-Mg adakites by crystal fractionation. Instead, they lie on trends that may reflect mixing lines between the average composition of the olivine-hosted melt inclusions and a high SiO_2, relatively low K_2O, end member. The trends are constrained by adakites from the Nungganungga volcanic unit (eastern Kadavu), and by the average composition of the magmatic enclaves within the western Kadavu adakite lavas. The petrogenesis of the Kadavu adakites therefore may be explained by mixing of an enriched high-Mg adakite with a typical low-Mg, SiO_2-rich adakite.

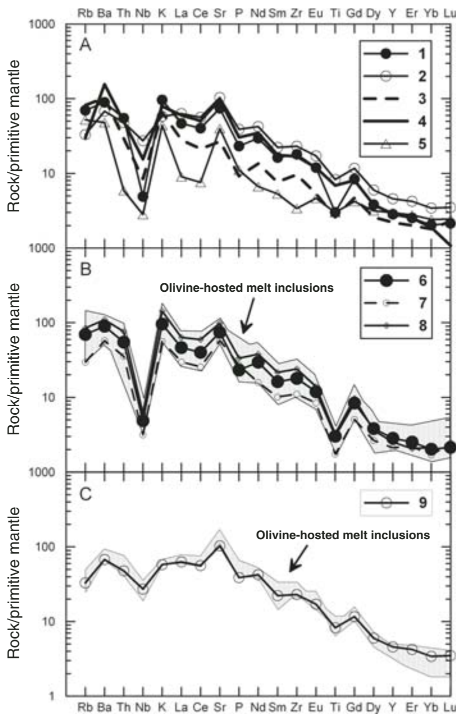

Figure 2. Primitive mantle normalized trace element abundances for the Kadavu high-Mg adakites ST44 (1) and NG1 (2). A: Compared to average low SiO_2 adakites (LSA) and high SiO_2 adakites (HSA) (3) and LSA (4) from Martin et al. (2005), and primitive shoshonite from Astrolabe Islands (AV186) (5) (Leslie, 2005). B: Range in olivine-hosted melt inclusions from east Kadavu high-Mg adakite ST44 (6); individual patterns for olivine hosts of $Fo_{84.6}$ (7) and $Fo_{93.1}$ (8) are also shown (see the Data Repository [see footnote 1]). C: Range in olivine-hosted melt inclusions from Ngaloa high-Mg adakite NG1 (9) (see the Data Repository). Primitive mantle values are from Sun and McDonough (1989).

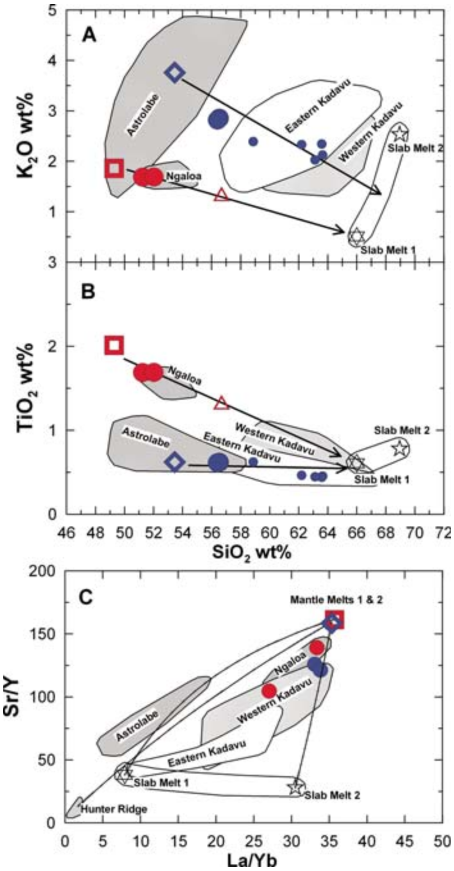

Figure 3. A: K_2O wt% versus SiO_2 wt% for adakite and shoshonite lava compositions from Kadavu Island Group. Blue symbols are lavas of Nungganungga volcanic unit: diamond—average composition of olivine-hosted melt inclusions in sample ST44; large circles—east Kadavu high-Mg adakites (ST44, ST43; Table 1); small circles—adakite lavas. Red symbols: square—average olivine-hosted melt inclusion in sample NG1; circles—Ngaloa high-Mg adakites (NG1, NG4; Table 1); triangle—average composition of enclaves within western Kadavu adakites. Thick black lines are interpreted mixing trends from primary mantle–derived high-Mg adakite and low-Mg adakite end member. Potential slab melt compositions are indicated as field encompassing slab melt 1 (pristine slab melt; Rapp and Watson, 1995) and slab melt 2 (average experimental slab melt; Zamora, 2000). For data sources, see Table 1 and the Data Repository (see footnote 1). B: TiO_2 wt% versus SiO_2 wt% for adakite and shoshonite lava compositions from Kadavu Island Group. Symbols and data sources as in A. C: Sr/Y versus La/Yb for adakite and shoshonite lava compositions from Kadavu Island Group. Also shown are model mixing lines between (1) average olivine-hosted melt inclusion composition from ST44 (mantle melt, blue diamond) and average Hunter Ridge tholeiite composition (Verbeeten, 1996), and slab melt 2, and (2) average olivine-hosted melt inclusion composition from NG1 (mantle melt 2, red square) and slab melt 1. Symbols and data sources as in A.

The high-Mg adakite end members likely result from melting of a slab melt-metasomatised mantle wedge. The differences in composition between the east Kadavu and Ngaloa high-Mg adakites may be explained by the prior history of the mantle wedge, which has been metasomatised by slab melts.

The low-Mg adakite end member may represent a direct melt from the slab; theoretical and experimental compositional estimates are shown in Figure 3. Evidence of the eruption of virtually unmodified SiO_2-rich slab melts has been reported from Tonga and the Trans-Mexican Volcanic Belt (Falloon et al., 2008; Rincon-Herrera et al., 2007). (For a discussion of alternative petrogenesis models for the Kadavu adakites, see the Data Repository.)

In summary, our discovery of rare high-Mg adakites from an adakite suite has the following two important implications. First, it suggests that high-Mg adakites are rarely erupted, and most likely evolve at depth or are involved in magma mixing processes within the magmatic plumbing system. Kelemen et al. (2003) provided evidence for the pervasive input from slab-derived melts into subduction-related magmas both in intra-oceanic and continental settings, and proposed that enriched high-Mg adakites are a significant mixing component into normal arc magmas. Second, we propose that, similar to other subduction-related magmas, adakites form a mantle-derived magmatic suite that includes both primitive high-Mg and more evolved low-Mg members. Within the suite, typical adakite chemical signatures become less prominent with decreasing MgO.

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